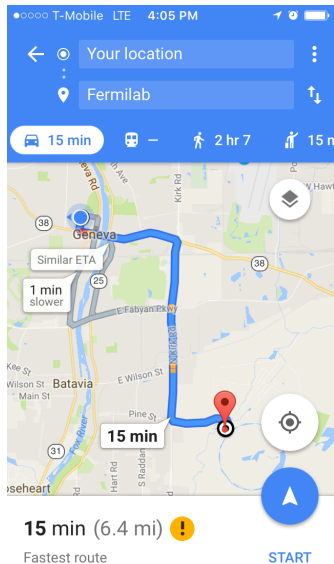


Building the world's most sensitive radio receiver to listen for dark matter

Daniel Bowring

May 7, 2017



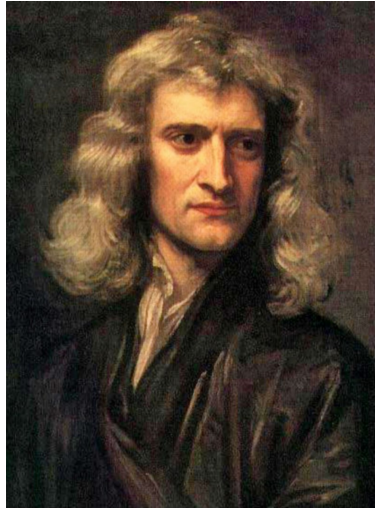
We have to account for Einstein's relativity in order to have accurate GPS.



- ▶ Each GPS satellite has a clock on it.
- ▶ Your phone knows how long it takes to receive a signal from multiple satellites.
- ▶ From there, it figures out where it is, relative to each satellite's position.

We'll get back to this in a minute.

When you think of gravity, who do you think of?

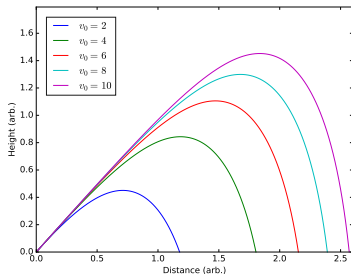


Godfrey Kneller's portrait of Isaac Newton, 1689

We all intuitively understand Newtonian gravity.

$$m \frac{d\vec{v}}{dt} = m\vec{g} - c\vec{v}$$

$$\frac{dv_x}{dt} = -g \frac{v_x}{v_t}$$
$$\frac{dv_y}{dt} = -g \left(1 + \frac{v_y}{v_t} \right)$$



You didn't need all that to catch a ball, though.

There's no limit to how much you can overthink this problem.

*Journal of Experimental Psychology:
Human Perception and Performance*
2002, Vol. 28, No. 2, 335–348

Copyright 2002 by the American Psychological Association, Inc.
0096-1523/02/\$5.00 DOI: 10.1037/0096-1523.28.2.335

Baseball Outfielders Maintain a Linear Optical Trajectory When Tracking Uncatchable Fly Balls

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Arizona State University West

Michael K. McBeath
Arizona State University

The authors investigated whether behavior of fielders pursuing uncatchable fly balls supported either (a) maintenance of a linear optical trajectory (LOT) with monotonic increases in optical ball height or (b) maintenance of optical acceleration cancellation (OAC) with simultaneous lateral alignment with the ball. Past work supports usage of both LOT and OAC strategies in the pursuit of catchable balls headed to the side. When balls are uncatchable, fielders must choose either optical linearity or alignment at the expense of the other. Fielders maintained the LOT strategy more often and for a longer period of time than they did the OAC alignment strategy. Findings support the LOT strategy as primary when pursuing balls headed to the side, whether catchable or not.

Ultimately, Newtonian gravity gets us a LOT.



We build bridges that stay up.

Ultimately, Newtonian gravity gets us a LOT.



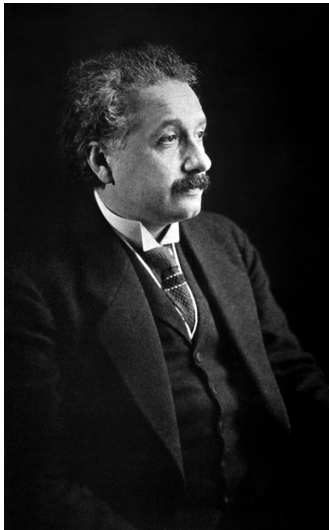
We launch and land rockets.

Ultimately, Newtonian gravity gets us a LOT.



It got us to the moon.

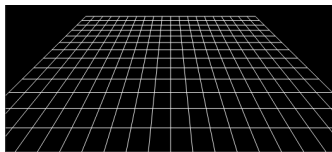
Outside of “normal” life, we need Einstein’s picture of gravity.



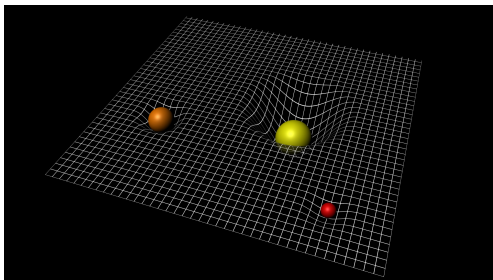
Here's what you need to know about Einstein's relativity.

- ▶ Imagine a satellite 20,000 km above the Earth, moving at 14,000 km/hour.
 - ▶ (Mt. Everest is 8.8 km high.)
 - ▶ (Airliners cruise at under 1000 km/hour.)
1. Time slows down when you move very fast.
(The clock on our satellite will run slower by $7\ \mu\text{s}/\text{day}$.)
 2. Time slows down when there's more mass around.
(The clock on our satellite will move faster by $45\ \mu\text{s}/\text{day}$.)
 3. All told, our satellite's clock "ticks faster" than your watch by about $38\ \mu\text{s}$ per day.
 4. This is not huge, but we need to correct for it or GPS won't work!

Einstein's relativity: space & time get distorted by mass.



No mass, spacetime is "flat".



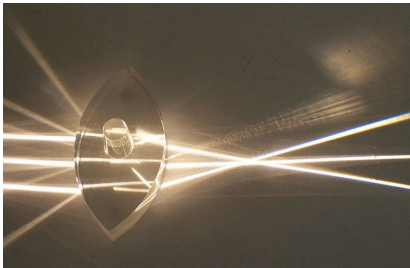
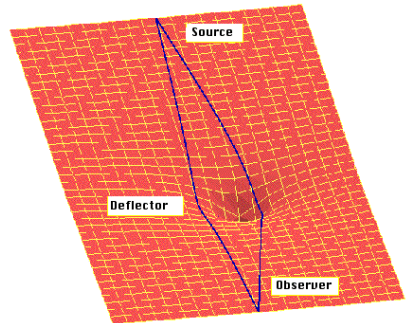
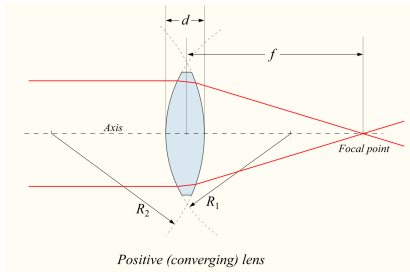
Massive objects distort spacetime.

$$g_{\mu\nu} = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

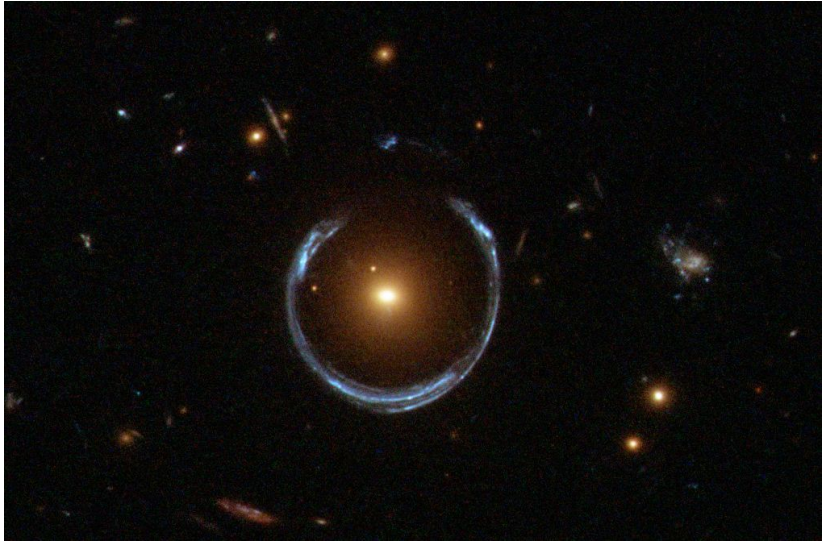
$$g_{\mu\nu} = \begin{bmatrix} \frac{2GM}{c^2 r} - 1 & 0 & 0 & 0 \\ 0 & \frac{1}{1 - \frac{2GM}{c^2 r}} & 0 & 0 \\ 0 & 0 & r^2 & 0 \\ 0 & 0 & 0 & r^2 \sin^2 \theta \end{bmatrix}$$

Mass M , $G = 6.67 \times 10^{-11} \text{ m}^3/\text{kg}/\text{s}^2$, r = distance from body.

What else bends light? Lenses.

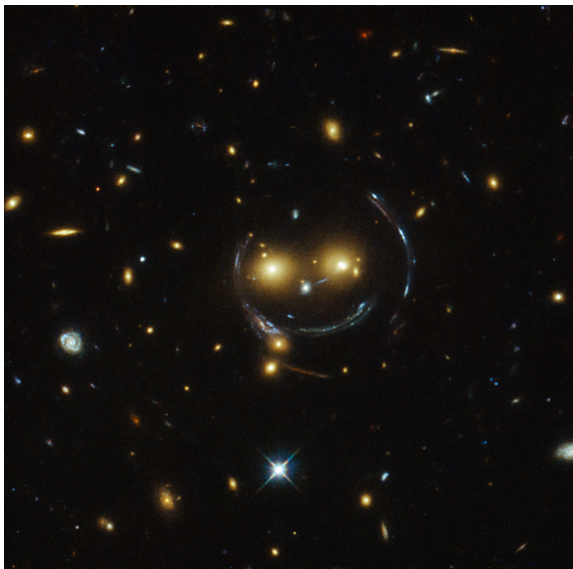


“Gravitational lensing” distorts astronomical observations.



Einstein ring, SDSS LRG 3-757

Another example of gravitational lensing



"Smiley", galaxy cluster SDSS J1038+4849

Now we are all experts on gravity.

- ▶ Newton suits our everyday experience.
- ▶ When things get very heavy or very fast, we need Einstein.
- ▶ Using this understanding, we have uncovered a mystery.

Most of the matter in the observable universe seems to be invisible.

First, some terminology.



This is a galaxy: UGC 12158, similar to our Milky Way

First, some terminology.



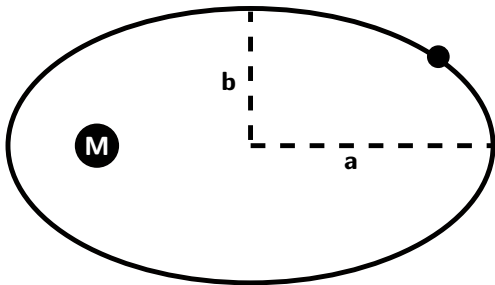
This is a cluster of galaxies. Abell 2744

Dark matter: a mystery in three acts

(Actually, way more than three acts, but we can't do this all day.)

1. We observe “non-Keplerian” motion in galaxies and clusters.
2. There's too much gravitational lensing.
3. Superhot clusters stay together when they shouldn't.

“Keplerian”: Johannes Kepler made some observations about the way planets move back in 1609.



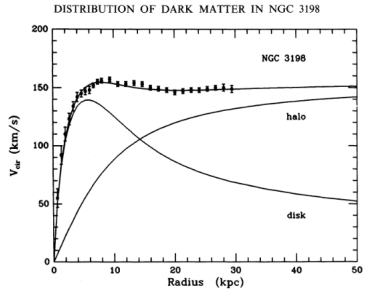
$$\frac{P^2}{a^3} \approx \frac{4\pi^2}{GM}$$

The farther a planet is from the sun,
the slower it moves.

Mystery 1: Some galaxies and clusters are non-Keplerian.



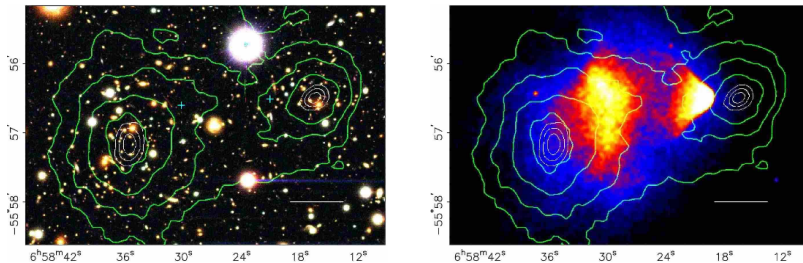
NGC 628



T.S. van Albada *et al.*, *The Astrophysical Journal* 295: 305-315 (1985).

Keplerian motion: lower velocities at larger radii. NGC 3198 shows velocity distributions that are very non-Keplerian.

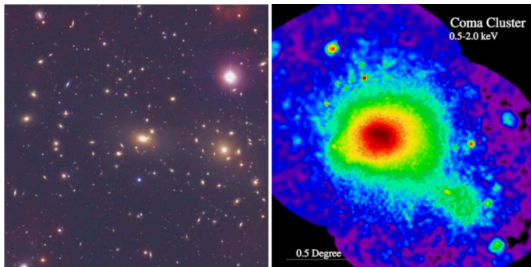
Mystery 2: There's too much gravitational lensing.



arXiv:astro-ph/0608407

- ▶ Left: Optical telescope (Magellan) image of two galactic clusters.
- ▶ Right: Chandra map of x-ray plasma (dominant visible mass).
- ▶ Green contours = mass distribution via gravitational lensing.

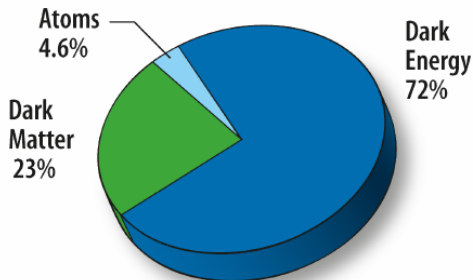
Mystery 3: There's too much mass in galactic clusters.



arXiv 0801.0968

- ▶ Density map of hot, x-ray-emitting gas in the Coma Cluster.
- ▶ What gravitational potential confines all this hot gas?
- ▶ “Missing mass” → dark matter.

All three mysteries are explained if there's some extra matter we can't see.

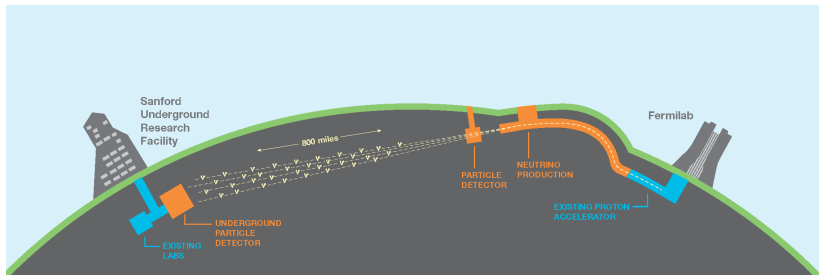


Quick break: Questions?

What is dark matter?

Dark matter is the name of a group of mysteries, but:

- ▶ It's some kind of matter.
- ▶ It should consist of new particles.
- ▶ The idea of invisible particles is not too far-fetched. What about neutrinos?



What kinds of particles are people looking for?

- ▶ Weakly Interacting Massive Particles (WIMPs)
- ▶ Undiscovered neutrinos
- ▶ Really exotic stuff (e.g. “extra-dimensional dark matter”)
- ▶ Axions

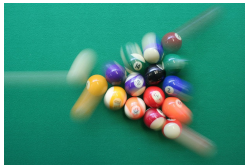
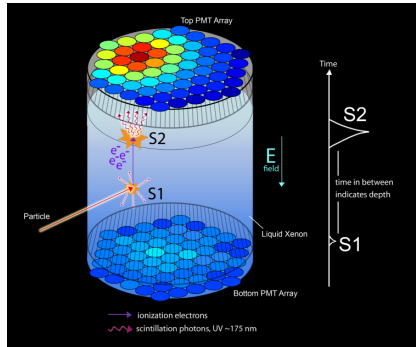
WIMPs and axions seem to be the most popular candidates right now.

[http://www.symmetrismagazine.org/article/
what-could-dark-matter-be](http://www.symmetrismagazine.org/article/what-could-dark-matter-be)

Searching for WIMPs is about looking for particle collisions.



http://lux.brown.edu/LUX_dark_matter/Home.html



What about axions?



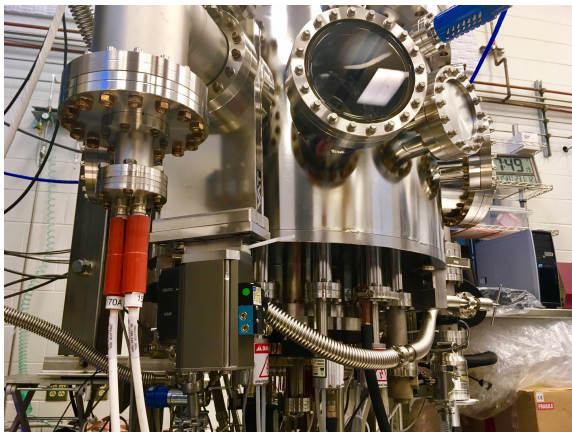
- ▶ “Light dark matter”
- ▶ Convenient to treat them like waves, not particles.

How should we search for axions?

Axions go wherever they want; they're all around us. So:

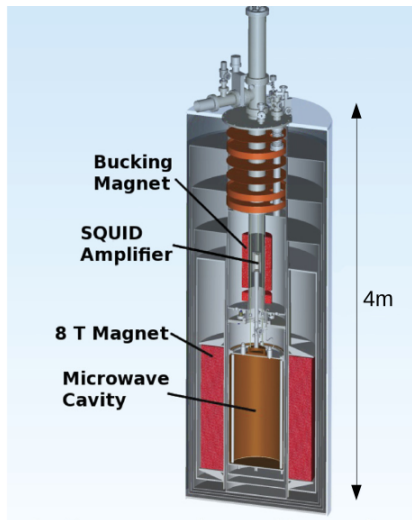
1. Make an empty box.
2. Ensure that only axions can get in the box.
3. Let axions convert into photons while inside the box.
4. Look for those photons.

Step 1: Make an empty box.



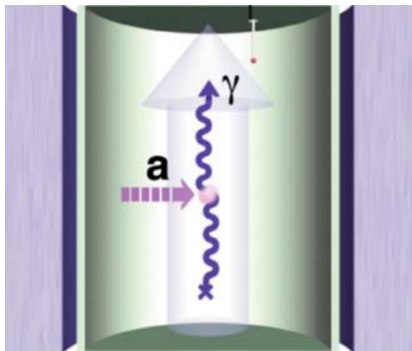
Very, very empty boxes are common in physics labs. We can pump chambers until they approach the pressure on the moon:
 $\gtrsim 10^{-14}$ atmospheres.

Step 2: Ensure that only photons can get into the box.



- ▶ “Light-tight” is good for visible light.
- ▶ Heat is a source of electromagnetic radiation.
- ▶ Make this box as cold as possible. 0.1 degrees above absolute zero!

Step 3: Let axions convert to photons in the box.



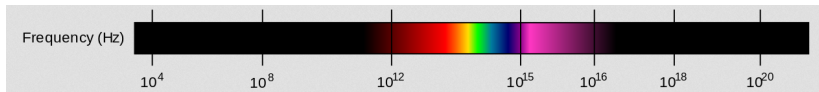
- ▶ Axions are everywhere, in theory.
- ▶ Strong magnetic fields (MRI-strength) should convert axions into photons.
- ▶ Put the box in a magnet.

Step 4: Look for photons.

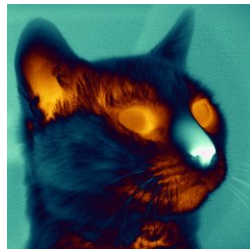
Photons resonantly accumulate in the box.

[Singing bowl video]

Our axion signal is photons in a box. But what frequency?



Radiation Type	Frequency
FM radio	100 MHz
Cell phones	1000 MHz = 1 GHz
Infrared light	10 million MHz = 10 THz
Visible light	400-800 THz
UV light	1 billion MHz = 1 PHz
X-rays	>10 PHz



<https://science.hq.nasa.gov/kids/imagers/ems/infrared.html>

Lots of choices for frequency. And theory doesn't narrow it down much.

$$E = mc^2 \rightarrow hf$$

- ▶ The mass of the axion is directly related to the frequency of the photons it creates via Planck's constant, $h \approx 6.62 \times 10^{-34}$ m²kg/s.
- ▶ Theory and observation narrow our search frequencies down to $200 \text{ MHz} < f < 200 \text{ GHz}$
- ▶ Imagine tuning a radio over three orders of magnitude!



The radio is actually a really good analogy.

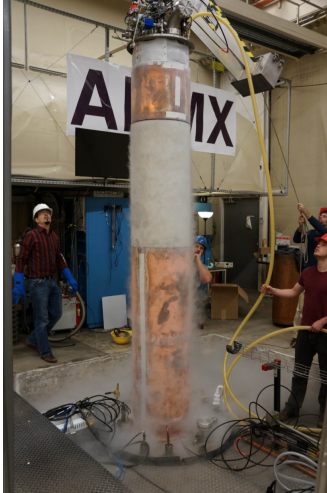
You're tuning a "radio" dial slowly, trying to match your detector frequency to the axion's photon frequency. But how good does your "reception" have to be? That is, how sensitive does your detector have to be?

- ▶ It's very hard to make axions convert into photons.
- ▶ When they do convert, it's hard to detect those photons. (There's not many of them.)
- ▶ You're looking for a very weak signal, then.
- ▶ "Four bars on Mars"

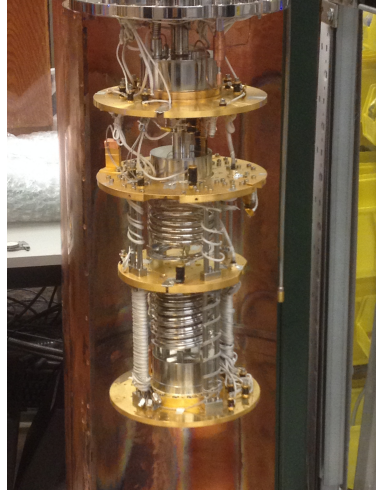
Let's review.

- ▶ There's a lot of matter in the universe that we can't see.
- ▶ We think axions might explain this dark matter.
- ▶ We look for axions by converting them into photons. . .
- ▶ . . .and then tuning our “radio” to look for the photon frequency.
- ▶ This radio has to be astoundingly sensitive.

The Axion Dark Matter eXperiment (ADMX)



Extracting a cold detector from its magnet



The experiment is cooled via a helium dilution refrigerator.

Fermilab is managing the ADMX project. We're excited to see what the future brings.



Thanks for your attention!